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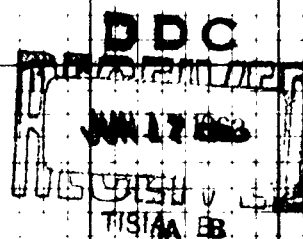
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**ADDENDUM**

**APPLIED RESEARCH ON TECHNIQUES  
FOR LIGHT MODULATION DETECTION**

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## SUMMARY

The relative advantages of convergent flow gun and linear flow gun traveling-wave phototubes are discussed in order to clarify those situations in which the former excels. Convergent flow guns are preferable in the following two situations, where we assume that the light signal is collected and focused onto the photocathode by a telescope of some kind: 1) The light source is not a point and the image is larger than the photocathode. In this case the receiver sensitivity is proportional to the cathode area. 2) The light source is effectively a point, e.g., a laser source. In this case the image may be smaller than the cathode, but the larger the photocathode, the less directional is the receiver --- an important consideration when the source and receiver cannot be perfectly aligned, and atmospheric effects cause virtual motion of the source. Satellite telemetry, and laser range finding systems are typical examples of this situation.

The effect of the acceleration region on the beam modulation is discussed by utilizing the results from low-noise TWT theory. The power output of the tube is not effected by the gun region in either a convergent or linear flow gun, provided the beam current is kept low enough, and the acceleration field and final beam voltage are kept high enough. These conditions are easily satisfied in the design of a phototube. Convergent flow guns are easily designed and constructed so that the cathode constant phase surface is transformed into a planar constant phase surface at the helix entrance. That is, with careful design, there is negligible variation in electron transit time to the helix entrance plane for electrons emitted from different parts of the cathode.

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## INTRODUCTION

The purpose of this addendum is to make explicit some of the considerations involved in the development of a convergent gun microwave phototube which heretofore have been tacitly assumed. It is felt that their explicit enunciation will help place in proper perspective the motivation and the direction of our developmental program. The discussion will center on two topics, a comparison of convergent gun phototubes with linear gun phototubes, and a discussion of the propagation of the beam modulation in the gun region. The former is necessary to clarify those applications in which a convergent gun tube is superior to a linear gun type. The latter is necessary for assurance that the beam transformations in the gun region will not degrade the signal which originates at the cathode.

## COMPARISON OF CONVERGENT GUN PHOTOTUBES WITH LINEAR GUN PHOTOTUBES

A convergent gun microwave phototube is completely equivalent to a linear beam tube except that it has the advantage of having a much larger cathode area. The tube we are presently developing has a cathode area ten times the beam area, and there is no apparent difficulty in developing tubes with area convergence ratios of 100:1 or greater, using the same techniques as we have used on the present tube. Thus, in the present tube, the cathode has a diameter of 0.200 in and future developments will produce one with a diameter of at least 0.700 in. Convergent guns will be even more important in millimeter wave traveling-wave phototubes because of the small beam diameters. For instance, Watkins-Johnson Company is presently developing a low-noise TWT for the range 80-115 Gc. This tube has a beam diameter of 0.004 in and a cathode diameter of 0.002 in. ( The beam is larger than the cathode because of transverse thermal velocities ).

The advantages of having a large photocathode area in applications which do not permit auxiliary light collection and focusing optics or which deal with optical images of substantial size, are obvious. Such situations are commonly encountered in the fields of nuclear physics, spectrophotometry, optical communications, and most other fields which must utilize light sources with extended areas. In all of these cases, the total light collected is proportional to the cathode area, hence, the signal to noise ratio is at least proportional to the cathode area. ( The signal to noise ratio will be proportional to the square of the cathode area when the noise is principally kTB noise in the helix because the signal out of the tube is proportional to the square of the beam current. When the noise is principally shot noise, which is proportional to beam current, the signal to noise ratio will be proportional to cathode area. )

For applications using light sources which are points for all practical purposes, such as a laser operating in a single transverse mode, the light can be collected and focused by auxiliary optics to an image size which, in the diffraction limited case, is proportional to the f number of the collecting optics. For example, the diameter of the diffraction limited Airy disk produced by a telescope with objective diameter D and focal length F is

$$d = \frac{2.44 Fd}{D} \quad (1)$$



Thus, for laser light with a wavelength  $\lambda = 6943\text{\AA}$ , and a Schmidt telescope or parabolic reflector with  $F = D$ , the diameter of the image is only  $1.7\mu$ . This is the minimum size and, in general, will be considerably larger because of aberrations and imperfections in the telescope. However, with high quality optics, it appears that the optical image of a laser source can usually be made at least as small as any feasible photocathode. For laser communication systems, the advantage that a convergent gun phototube has is not that of increased light collection, since that can be done by auxiliary optics. It will be most advantageous in applications where a relatively non-directional receiver is required, such as in many laser telemetry systems, laser search radars, etc.

For instance, consider the receiver geometry of Fig. 1, consisting of a reflector for light collection, a small plane ( or spherical ) mirror, and a phototube. The maximum off-axis angle  $\Theta$  at which light can be detected is given by

$$\Theta = \frac{d}{2F} \quad (2)$$

where  $F$  is the focal length of the telescope, and  $d$  is the diameter of the photocathode. If we consider the reasonable values of reflector diameter  $D = 30\text{ cm}$ ,  $F = 30\text{ cm}$ , and  $d = 6 \times 10^{-2}\text{ cm}$  ( corresponding to a linear gun X-band phototube ), then  $\Theta = 10^{-3}\text{ rad} = 3.4\text{ min. of arc}$ . This receiving angle can be increased by a factor of 10 to  $34\text{ min.}$ , by the use of a convergent gun phototube. For a millimeter wave linear gun phototube with  $d = 6 \times 10^{-3}\text{ cm}$ , the maximum receiving angle will be  $21\text{ sec. of arc}$ , and this can be increased by a factor of 10 to  $3.4\text{ min. of arc}$  with the use of a convergent gun phototube. The advantages of a convergent gun phototube are clear for systems where the extreme directionality imposed by the use of small photocathodes are not desired. It should also be added that less expensive collecting optics can be used when a large photocathode is available because the quality of the image used not be so high.

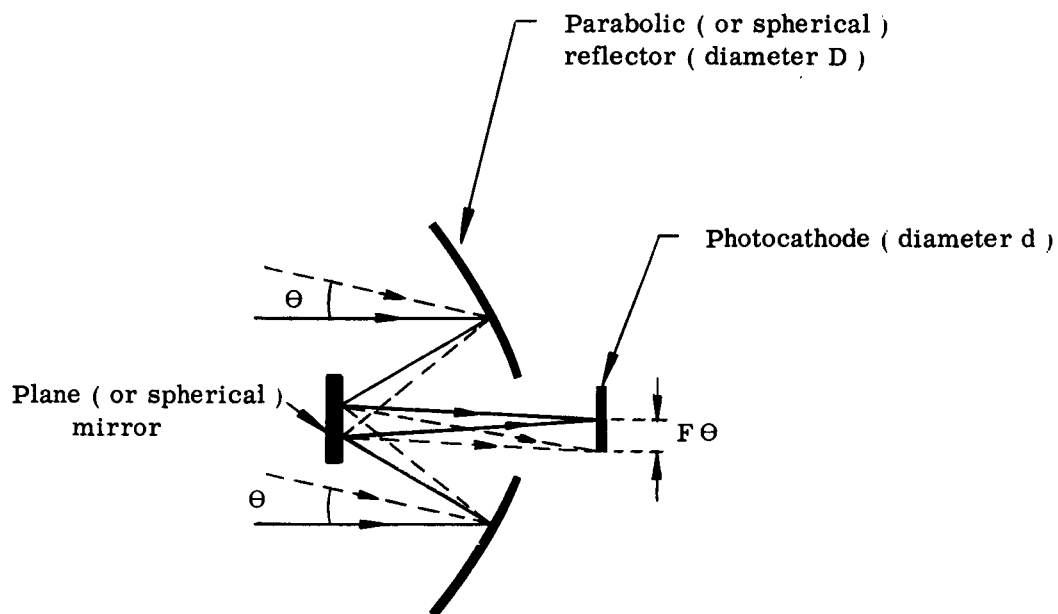


Fig. 1 - Geometry of optical receiver consisting of a spherical reflector, plane mirror, and phototube. The photocathode size limits the angle  $\theta$  of the received light to a value  $\theta = \frac{d}{2F}$ .

## PROPAGATION OF THE SIGNAL ON THE ELECTRON BEAM IN THE GUN REGION

In any microwave phototube, some consideration of the propagation of the electron beam modulation in the gun region is necessary in order to assure oneself that the signal will not in some way be attenuated between the cathode and microwave circuit. An approximate analysis can easily be made by utilizing the well established theory that has been developed during the course of studies of noise reduction techniques for TWT's.

It is necessary for this purpose to review briefly some of the theory of signal propagation on thin electron beams. If  $U$  is the amplitude of the ac kinetic voltage modulation, and  $I$  the amplitude of the ac current modulation, then the equations governing these quantities are<sup>1</sup>

$$\frac{d^2 U}{d\phi^2} - \frac{1}{W} \frac{dW}{d\phi} \frac{dU}{d\phi} + U = 0 \quad (3)$$

$$\frac{d^2 I}{d\phi^2} + \frac{1}{W} \frac{dW}{d\phi} \frac{dI}{d\phi} + I = 0 \quad (4)$$

where

$$\phi = \int_0^z \beta_q(z) dz$$

$$\beta_q = \frac{p \omega_p}{u}$$

$$\omega_p = \text{plasma frequency}$$

$$p = \text{plasma frequency reduction factor}$$

$$W = \frac{2 V_o}{I_o} \frac{\beta_q}{\beta_c}$$

$$V_0 = \text{dc beam voltage}$$

$$I_0 = \text{dc beam current}$$

$$\beta_e = \frac{\omega}{u}$$

Equations 3 and 4 can be solved for the gun region only if  $W$  is a function of  $\phi$  is known. For many potential profiles, it is convenient to assume that  $W$  varies exponentially<sup>2</sup> with  $\phi$ , i.e.,

$$W = W_a e^{k\phi} \quad (5)$$

$$\frac{1}{W} \frac{dW}{d\phi} = k \quad (6)$$

where  $k = \text{const.}$  The above assumption about  $W$  implies a potential profile that is slightly super-linear in the acceleration region.<sup>2</sup> Even if, in any actual tube, the exponential variation of  $W$  does not hold, some general conclusions can be drawn that will be true for a large variety of potential profiles by assuming Equations 5 and 6.

Equations 3 thru 6 imply a lossless transformation of the values of  $U$  and  $I$  between two planes  $a$  and  $b$  according to the following matrix equation<sup>2</sup>

$$\begin{bmatrix} \frac{U_b}{I_b} \end{bmatrix} = \underline{\underline{M}} \begin{bmatrix} \frac{U_a}{I_a} \end{bmatrix} \quad (7)$$

where

$$\underline{\underline{M}} = \begin{bmatrix} \frac{e}{m} \frac{k\phi}{2} (m \cos m\phi - \frac{k}{2} \sin m\phi) & j \frac{W_a}{m} e^{\frac{k\phi}{2}} \sin m\phi \\ \frac{j}{W_a m} e^{\frac{-k\phi}{2}} \sin m\phi & \frac{1}{m} e^{\frac{-k\phi}{2}} (m \cos m\phi + \frac{k}{2} \sin m\phi) \end{bmatrix}$$

$$m = \left[ 1 - \left( \frac{k}{2} \right)^2 \right]^{1/2} \quad \text{and} \quad \phi = \phi_b - \phi_a$$

We also have

$$\frac{W_b}{W_a} = \frac{p_b}{p_a} \frac{b_a}{b_b} \left( \frac{V_{oa}}{V_{ob}} \right)^{3.4} = e^{k\phi} \quad (8)$$

where  $b$  is the beam radius. We see that for practical phototubes, using  $a$  as the cathode plane, and  $b$  as the helix entrance plane,

$$\frac{W_b}{W_a} \gg 1 \quad (9)$$

and that for large accelerating fields

$$k \gg 1. \quad (10)$$

In fact, the gun in our tube can be roughly characterized by values of

$$\frac{W_b}{W_a} \approx 200$$

while, if we assume a beam current of  $1 \mu\text{amp}$ ,

$$k \approx 100.$$

Thus, assuming (9) and (10) to be valid, the matrix M can be simplified to

$$\underline{\underline{M}} \approx \begin{bmatrix} 1 & \frac{j W_b}{k} \\ \frac{j}{k W_a} & 1 \end{bmatrix} \quad (11)$$

At the cathode plane we have  $U = U_a = 0$  and  $I = I_a$ . Thus, at the helix, we have, using Equation 11:

$$U_b \approx \frac{j W_b}{k} I_a \quad (12)$$

$$I_b \approx I_a \quad (13)$$

The current modulation has been unchanged by the gun, but some velocity modulation has been added, 90 degrees out of phase with the current modulation. However, the velocity modulation will have little effect on the power out because of the small factor  $\frac{1}{k}$  which is about 0.01 for our tube. Thus  $U_b$  can be neglected, and the conditions at the helix entrance plane are essentially those at the cathode. The above considerations apply also to the noise modulation at the helix due to shot current modulation at the cathode. Thus, the signal-to-noise ratio is essentially the same at the helix as it is at the cathode.

The theory of exponential transformers shows that, for a fixed beam and gun geometry,<sup>2</sup>

$$k \propto I_0^{-\frac{1}{2}} \quad (14)$$

Thus, we can estimate the values of  $I_0$  for which (10) no longer holds. In our case, if  $I_0$  exceeds values of about  $400 \mu\text{amp}$ ,  $k$  becomes less than 5 and the matrix  $\underline{M}$  no longer simplifies to Equation 11. We can regard this value of current to be an upper limit above which a more careful analysis and design of the gun will be necessary. At such current levels, space-charge limited flow must be prevented. For most detector applications, the beam currents will be far below this limit and we need not concern ourselves with it.

Even though an electron gun may not be precisely an exponential type, the above analysis holds in a qualitative manner for potential profiles which monotonically increase with distance. It is clear that what is important is the value of

$$\frac{1}{W} \frac{dW}{d\phi}$$

throughout the acceleration region. If this quantity is at every point much larger than unity, and if (9) holds then the magnitude of the ac current at the cathode will be transformed into the same magnitude at the helix while the conversion to voltage modulation will be negligible. We note that these criteria do not place any upper limits on the values of  $\phi$ . The gun can be any arbitrary number of wavelengths long provided that

$$\frac{W_b}{W_a} \quad \text{and} \quad \frac{1}{W} \frac{dW}{d\phi} \gg 1 .$$

## REFERENCES

1. A review of this problem is given by H. A. Haus, Noise in Electron Devices, edited by L. D. Smullin and H. A. Haus ( Technology Press of MIT and John Wiley and Sons, New York, 1959 ) Chapter 3.
2. A review is given by R. W. Peter, Chapter 5 of Reference 1.

## APPENDIX

The following is a chart showing the approximate beam diameters of traveling-wave phototubes for different frequency bands, and the area convergence ratios required for a cathode diameter of 0.200 inch.

<u>Frequency Band</u>	<u>Beam Diameter</u>	<u>Area convergence ratio for 0.200 inch cathode</u>
1 - 2 Gc	.075-.100 in	4-7
2 - 4	.040-.070	8-25
4 - 8	.034	35
8 - 12	.018	120
12 - 18	.015	180
18 - 25	.012	280
26 - 40	.009	490
40 - 60	.005	1,600
60 - 90	.002	10,000



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